A Sensorless Position Estimator for a Nonlinear Solenoid Actuator

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Abstract- **The proportional solenoid is a variable reluctance actuator operating under trajectory or position control mode. Established sensorless position estimation methods for variable reluctance motors do not work on proportional solenoids due to its single phase structure, non-cyclic electrical signals, unpredictable load variations and highly nonlinear model. In this paper, a novel method of estimating the position of a solenoid by indirect observation of incremental inductance in the excited coil is described. The method relies on accurate measurement of *di/dt* values. For this purpose, a novel hardware circuit which measures the *di/dt* values from PWM current waveform accurately and reliably is developed. The method is implemented on a DSP and the results are found to be satisfactory.**

1. INTRODUCTION

Solenoids are widely used as switching actuators. They are simple in construction, rugged, and relatively cheap to produce. For these reasons they can be found in many industrial and domestic apparatus in which limited stroke, on/off mechanical movements are required. On the other hand, conventional proportional actuators are high precision, limited travel motional devices, driven by step motors, moving coil actuator, or other motors with a linear control characteristic. Such proportional actuators are more complex in construction, contain delicate moving and sensing elements, and are expensive to produce and maintain. These actuators are used in high end applications in which precise control over the movements of the actuator is required.

This paper describes part of a project which aims to convert switching solenoids into proportional actuators by the use of intelligent control. The control aspect of this task has been successfully accomplished and is reported in [1,2]. The next research stage is to eliminate the position sensor inside the proportional solenoid, so that a more robust and lower cost proportional actuator can be constructed. Fig. 1 is a typical construction of a two stage solenoid valve. The total travel of the plunger is very short: in most cases it is below 1 centimetre. Since fluid flows all around the plunger, and the area is totally sealed, there is little space to mount a position sensor inside the solenoid. Therefore sensorless position detection is a very attractive proposition.

Presently, there is much research work done on sensorless position estimation of variable reluctance motors.

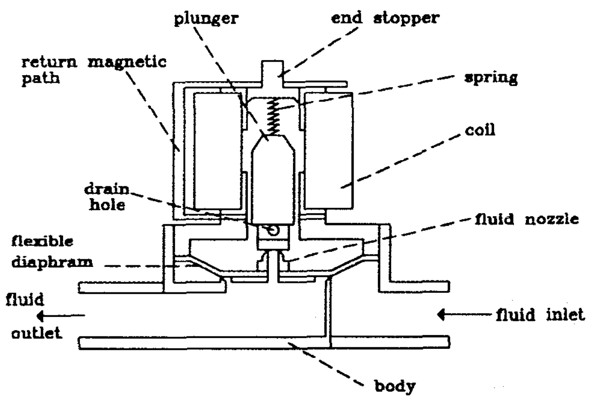

Fig.1 Construction of a two stage solenoid valve

Unfortunately, none of these methods are suitable for use in solenoid actuators. Some methods can only work on multi-phase machines, because they require an inactive phase for signal injection [3] or require inductance measurement at near zero current level [4]. Other methods require continuous integration to calculate flux linkage [5,6]. However, these methods are only suitable for cyclic electrical signals, as in rotary machines, because offset error can be compensated easily. Unidirectional electrical signals, as in the case of solenoids, cannot be compensated readily and will cause problems of integration runaway. Recently, there has been much work done on position estimation based on the state observer's principles [6]. However, solenoids' control characteristics are highly non-linear and complex to model [7]. Also, mechanical loads of solenoids vary greatly with external factors, and are difficult to predict and model. To implement a non linear position observer based on the solenoid's complex control model is not practical and unreliable

2. POSITION ESTIMATION FOR SOLENOID ACTUATORS

A. State Equations of the Solenoid

To develop a sensorless position estimation method for the solenoid actuator, the first step is to investigate the control characteristics of the device. The state equations for the solenoid actuator is shown in (1) to (4):

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$$\frac{dx}{dt} = v \quad (1)$$

$$\frac{dv}{dt} = \left(F(x,i) - K_s x - m_p g\right) \cdot m_p^{-1} \quad (2)$$

$$\frac{di}{dt} = \left(V - Ri - K_v(x,i) \cdot \frac{dx}{dt}\right) \cdot L(x,i)^{-1} \quad (3)$$

where $F(x,i) = \frac{\partial \lambda(x,i)}{\partial i} \cdot i \qquad K_v(x,i) = \frac{\partial \lambda(x,i)}{\partial x}$

$$L(x,i) = L_e + \frac{\partial \lambda(x,i)}{\partial i} \quad (4)$$

In the state equations, m_p and x are the mass and position of the plunger, V and i are the terminal voltage and current of the solenoid, R is the coil resistance, K_s is the spring constant, g is the gravitational acceleration, L_e is the leakage inductance, $F(x,i)$ is the force produced by the magnetic field, $K_v(x,i)$ is the motional e.m.f., and $L(x,i)$ is the incremental inductance of the solenoid.

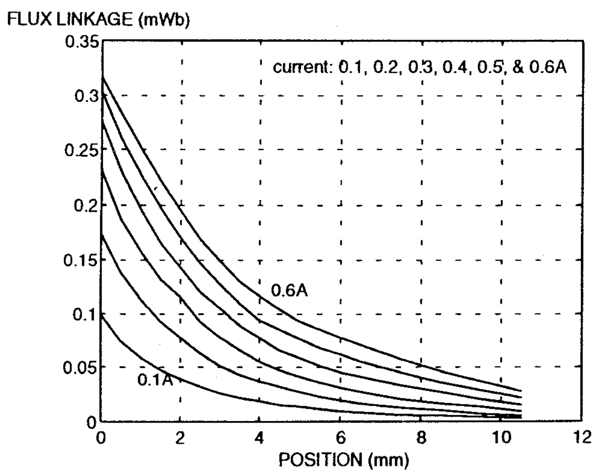

Fig.2 Flux linkage vs position at different currents

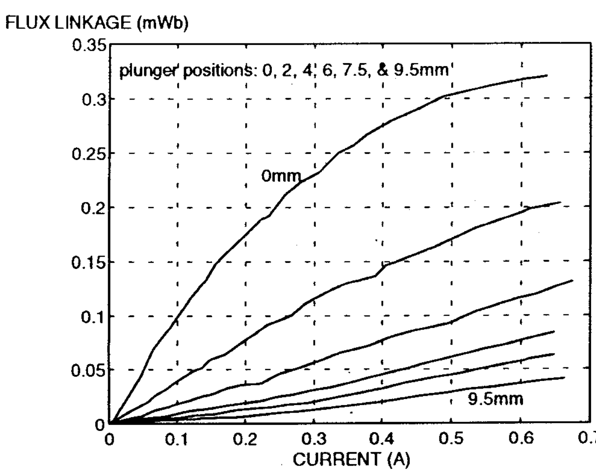

Fig.3 Flux linkage vs position at different positions

The state equations also include the nonlinear characteristics of flux linkage λ versus current i and position x. These relationships can be obtained experimentally [8] and are of the form shown in Fig. 2 and Fig. 3.

B. The proposed position estimation method

Equation (1) and (2) describes the mechanical dynamics of the solenoid, while (3) is the solenoid's voltage equation. External loading of a solenoid is unpredictable, and it affects the mechanical dynamics of a solenoid significantly. Therefore (1) and (2) do not provide an accurate and predictable description on the position of the solenoid. Therefore only (3) is used for position estimation. Equation (3) is rearranged into the following form:

$$L(x,i) = \frac{V - Ri - E(x,i)\frac{dx}{dt}}{\frac{di}{dt}} \quad (5)$$

From the simulations of the proportional solenoid [12], it has been found that the motional e.m.f. term $E(x,i)\frac{dx}{dt}$ only contributes a maximum of 2% of its value in relation to $V - Ri$ under normal operation. Under this circumstance, (5) can be rewritten as:

$$L(x,i) = (V - Ri)\left(\frac{di}{dt}\right)^{-1} \quad (6)$$

Therefore sensorless position estimation of the solenoid can be achieved by measuring the electrical quantities of V, i, and di/dt and by calculating the incremental inductance $L(x,i)$. From the incremental inductance, position x can be inferred from a two dimensional look-up table of $x(L,i)$.

Equation (6) is meaningful if di/dt is non-zero and significantly large. For the case of a proportional solenoid, there are times when the plunger is stationary and the current change is zero. To resolve this, di/dt is measured from the current rise of the PWM current waveform, instead of differentiating the average current i to obtain the di/dt value. Since the positive chopping voltage is much higher than the maximum operating voltage of the solenoid [1,2], di/dt is always significant and non-zero.

Fig. 5 is the plot of incremental inductance versus position at various current levels. At low level currents of 0-0.1A, inductance decreases substantially as air gap position is increased. However, when current level is increased, the rate of inductance change is reduced. As current is increased to 0.2A or above, saturation occurs, and L behaves differently.

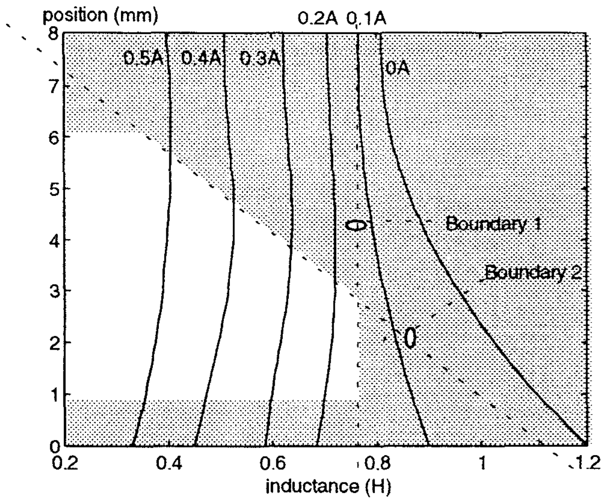

Fig.5 Incremental inductance versus position and current for a solenoid

At higher current values (0.2A), when the plunger position increases, the inductance increases accordingly, then at certain point, decreases again due to saturation.

In Fig. 5, two boundaries are used to mark out the area which is suitable for position estimation. Boundary 1 divides the operation of a solenoid into saturation (high current) and non-saturation (low current) regions. The non-saturated region is only useful for position estimation of multi-phase VR motors, when an unenergised phase is available. The proportional solenoid normally operates at high current region of 0.2-0.6A [1,2]. Boundary 2 is used to restrict the operation of position, so that unique position estimations can be obtain from current and inductance inputs. Combining the two boundaries, position estimation is restricted to the unshaded area of Fig. 5. and the solenoid actuator is limited to 1-6 mm of plunger travel.

For large position (e.g. 6mm) and small current (0.2A), operation is outside the position estimation range, because it falls into the shaded area. However, this situation never occurs because high current is required to drive the plunger when position is large. Although the solenoid can be operated with a stroke length of 5mm (i.e. 1-6mm) only, it is already very useful, and can readily cope with many industrial applications.

C. *A Novel Hardware Circuit to Measure di/dt*

The success of the proposed position estimation scheme depends heavily on accurate measurement of *di/dt*. There is little in recent literature which provides a reliable and accurate solution to measure *di/dt* for PWM waveforms. Acarnley *et. al.* [9] determines the current rise of a chopping waveform by measuring the frequency of the hysteresis current controller. However, the method is unsuitable for fixed frequency PWM output with a sophisticated current control strategy, as in the case of proportional solenoid. Panda and Amaratunga [10] has suggested a hardware circuit to detect the current rise of a fixed frequency PWM waveform, but the method is not suitable for continuous position estimation. Kulkarni and Eshani [11] has suggested a position estimation scheme for permanent magnet synchronous motors by measuring its *di/dt* values, but there is no indication on how this method can be implemented in practice, particularly in measuring *di/dt*. Consequently, only the simulation result is published. The main difficulties for *di/dt* capture are:

(i) The processing of high frequency PWM.
(ii) The synchronisation of high frequency waveforms.
(iii) The relatively small magnitude of *di/dt* when compared to the absolute current value.
(iv) The noise associated with measuring differential signals.

In this paper, a novel circuit to measure the *di/dt* value from the PWM current waveform is proposed. The circuit provides the following functions:

(i) It removes the current offset and brings the starting current at the beginning of each PWM cycle down to zero potential.
(ii) It synchronises the current capture time with the PWM waveform.
(iii) It measures the sum of a number of current rise waveforms during a number of PWM periods. In this way an average current rise value during a particular sampling period can be obtained. This measurement concept is explained in figure 6.

The block diagram of the current rise measurement hardware is shown in Fig. 7. The circuit is a combination of four separate functional blocks: offset elimination, summation and capture, timing and synchronisation, and computer handshake. The hardware has two analogue inputs to measure the solenoid's voltage and current. It is connected to the DSP by an analogue output and two handshake lines. The output gives the summation of total current rise Δi during a specific and pre-defined time Δt.

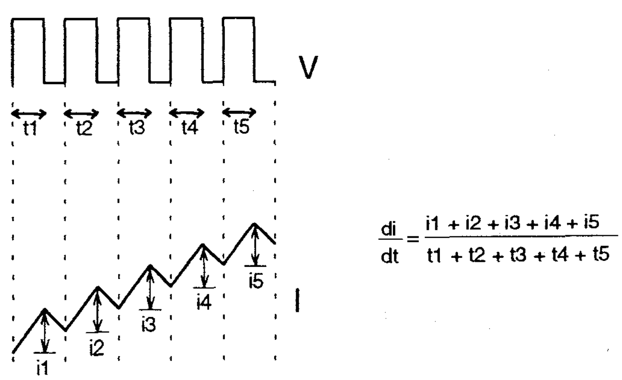

Fig.6 Finding the average current rise for a number of PWM cycles

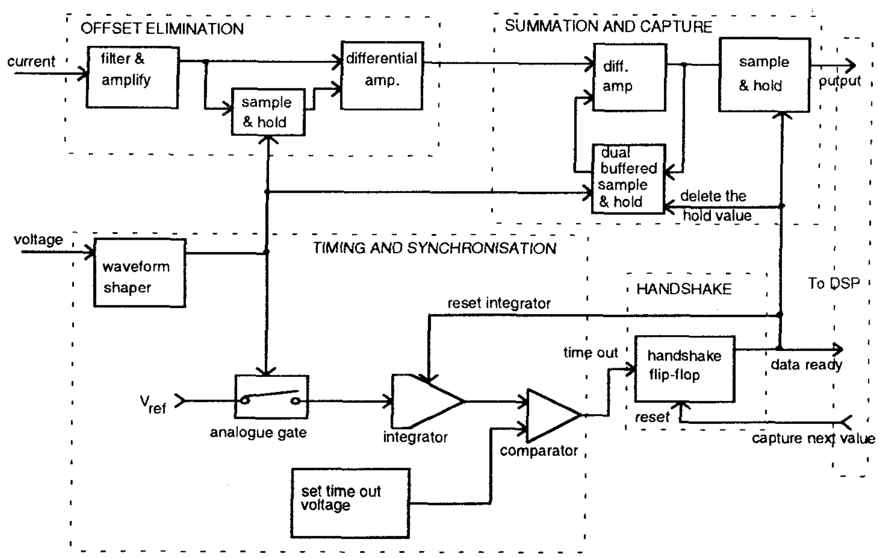

Fig. 7 Block diagram of the current rise measurement circuit

The offset elimination block amplifies the current signal, sample its reference point, then brings it down to zero. In this way, offset current is eliminated. Only the positive PWM cycle is used for the current rise measurement. The signal waveforms for such a measurement process is illustrated in Fig. 8.

The summation and capture block sums up the values of current rise within a specific number of PWM cycles. By adding all the current rise waveforms within a control loop sampling period, and by calculating the average *di/dt* value, accuracy is increased and noise is reduced. For the proportional solenoid, the PWM frequency is 12.5 times faster than the outer loop frequency. Allowing time for data transfer and synchronisation, there is still enough time to capture approximately 10 current rise waveforms within a control loop sampling period.

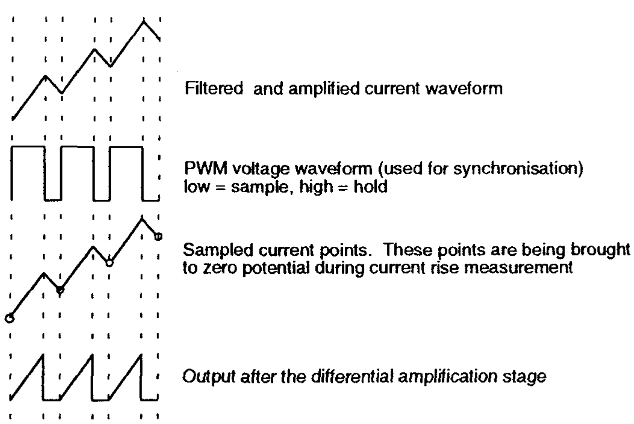

Fig. 8 Signal waveforms of the offset elimination block

Fig. 9 is the detailed block diagram of the summation and capture block. It contains a double sample and hold circuit configured as feedback elements to the differential amplifier. The previous output of the differential amplifier is used as a reference potential for the next current rise capture. The two sample and holds are arranged in such a way that when one is sampling, the other one is on hold. The two sample and hold circuits are synchronised to the PWM waveform, so that when current rise occurs, the reference voltage is on hold at the differential amplifier input.

When a specified number of current rise has been captured, the total current rise value will be transferred to another sample and hold circuit for output to the DSP. The circuit holds the output until the value is acquired by the ADC of the computer. At the same time the sample and hold in the feedback path is cleared by selecting the analogue switch to ground level. Signal trace for the summation and capture circuit is shown in Fig. 10.

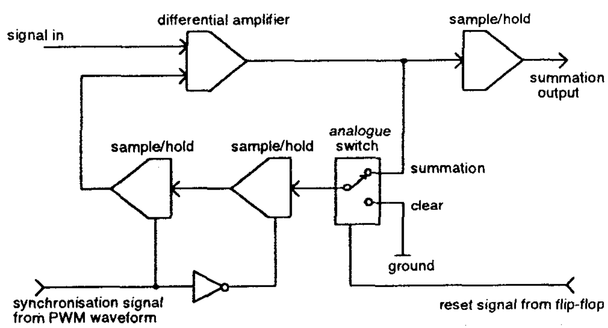

Fig.9 The summation and capture block

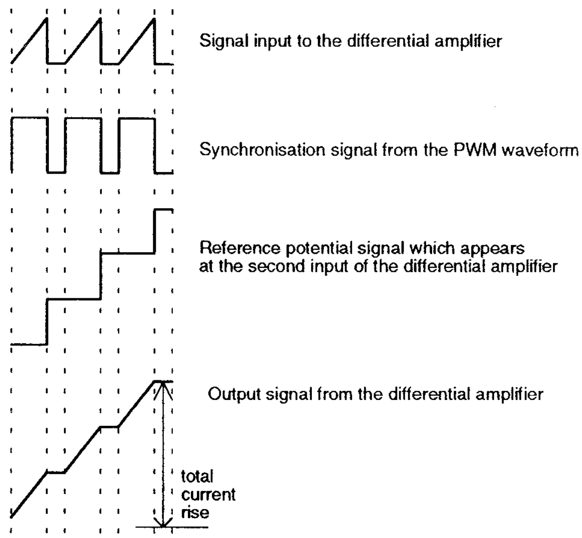

Fig.10 Signals of the summation and capture block

The handshake block ensures that the current rise measurements are transferred to the DSP reliably. A standard two line ("data ready" and "next capture") handshake protocol is used. When "data ready" is active, the integrator is reset, the sample and hold circuit in the feedback path is cleared, and the captured data is transferred to a sample and hold circuit in the output stage.

The synchronisation block synchronises the current rise capture time with the PWM waveform. The PWM waveform passes through a zero detection circuit; and from this circuit a synchronisation signal is constructed. This signal is fed to the timer block keep track of the time timing of Δt The signal is also connected to other parts of the circuit for synchronisation.

The timer block measures the duration of the positive PWM cycle. When the synchronisation signal is positive, the analogue gate causes the output voltage of the integrator to rise. The integration stops when the PWM cycle changes to off state. When the output voltage of the integrator has increased to the preset value, a time out signal is issued to the DSP. This signifies the end of a waveform capture cycle. The time duration is preset by the user by adjusting V_{ref}.

To ensure that the captured waveform is available to the DSP when requested, the duration of current rise capture should be set according to the condition stated in (7):

$$t_1 < \frac{t_2}{2} - t_3 \tag{7}$$

where t_1 is the duration of current rise capture, t_2 is the sampling period of the outer control loop, and t_3 is the time required for data to transfer from the measurement hardware to the DSP.

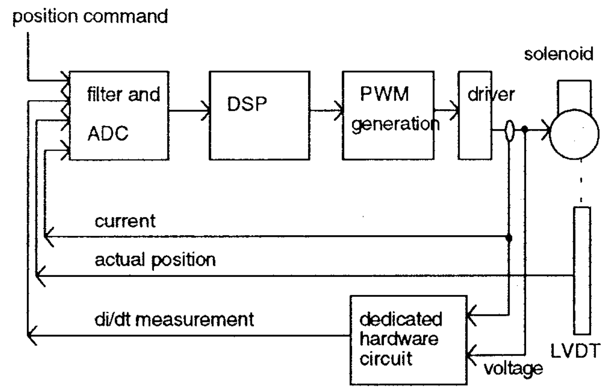

Fig.11 Setup of the position estimation experiment

Essentially, the equation assumes that the PWM duty cycle is always above 50%, because the terminal voltage is always unidirectional [1,2]. On top of (7), a small safety margin should be allowed for additional delays in the hardware circuitry, and the tolerances of timing in the DSP.

3. IMPLEMENTATION

The overall structure of the experimental setup is shown in Fig. 11. Basically it is a proportional solenoid controller [1,2] plus a dedicated current rise measurement circuit to capture the *di/dt* values. In the experiment, the DSP uses the values of *V, i,* and *di/dt* to estimate position in real time.

The incremental inductance values are stored in a two dimension look-up table *L(x,i)* with current and position as rows and columns of indices. Position and current increments of 0.5mm and 0.05A are used (i.e. a table size of 25×25), and bi-linear interpolation is used to find the intermediate values. This arrangement creates a maximum tolerance of 2% only.

The estimated position, together with the actual position are recorded in a trace module for further analysis. Apart from position estimation, the DSP also executes the nonlinear proportional control scheme concurrently and in real time.

4. RESULT

Fig. 12 is the result of position estimation when implemented in hardware. The trajectory path of the plunger and the estimated position are both shown in the same graph. In the experiment, a triangular waveform with a period of 1 second and a peak to peak travel of 1-6mm is used as the input command for the proportional controller.

Overall, the estimated position resembles the trajectory path. The estimated position is noisy around 5-6 mm region. This is due to the low gradient profiles of the incremental inductance versus position curves in that region, as shown in Fig. 5.

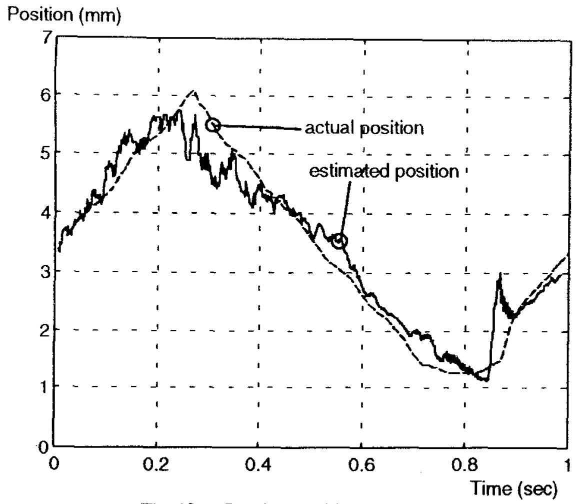

Fig. 12 Result of position estimation

Though hysteresis does not cause significant reduction in accuracy, its does have an effect on the estimated position when a large change in current direction occurs. It causes a 'kick' in the estimated position. Change of resistance due to temperature rise will also affect the accuracy of position estimation. It has an effect of slightly shifting the estimated position curve upwards or downwards. However, this affect can easily be compensated by periodic calculation of actual resistance during static or slowly moving voltage and current waveforms. Unlike speed controlled variable reluctance motors, a position controlled proportional solenoid experience many periods of near static current and voltage waveforms during its operation.

Though the present result of position estimation still contains a small amount of noise and there are limitations on the position estimation range, it is already very useful for low resolution position estimation, especially when the solenoid operates as a valve, and the plunger is totally immersed in fluid.

6. CONCLUSION

This paper identifies the sensorless position estimation scheme of a solenoid through detail investigation into the control model of the device, and locates the part of the model in which position estimation is most appropriate. It then proposes to estimate position indirectly through incremental inductance, exploiting the fact that motional e.m.f. is insignificant under normal operation condition. This paper also describes a novel circuit to measure the *di/dt* values of PWM current waveforms accurately and reliabily. The circuit is not complex and can be readily condensed into a programmable cell array chip. Also, the circuit does not need any assistant from the DSP.

Results of hardware implementation shows that the estimated position resembles the actual position trajectory, although the result is slightly noisy. In spite of this, it is already very useful for low resolution position estimation of solenoids, especially in cases when mounting of position sensor is not feasible. This method is also suitable for any slow moving single phase variable reluctance motors. Generally, the accuracy of the proposed position estimation method is dependent on the inductance-position-current characteristics of the device. A device with a higher inductance-position gradient gives better estimation result.

5. REFERENCES

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